1 Pau Amaro Seoane

1.1 Title

Sculpting the Galactic Centre

1.2 Abstract

Recent observations have revealed various structures within the gravitational influence of Sgr A* that apparently defy the fundamental principles of star formation and stellar dynamics. On one hand, the red giants display a flat density profile, contrary to the cuspy one predicted by conventional stellar relaxation. On the other, Wolf-Rayet and OB stars are observed where in-situ star formation should have been prohibited by the strong tidal force from Sgr A*, and their spatial and phase-space distributions also contradict our understanding of stellar dynamics. To explain each of these features, many scenarios have been proposed, which render the model increasingly complicated. I suggest that the sub-parsec stellar disk surrounding Sgr A*, which was recently discovered, can reconcile all the above inconsistencies. I show that during the fragmenting past of this disk, the star-forming clumps could efficiently deplete red giants by repeatedly colliding with them. I also show that because of the torque exerted by the disk, stars within the central arcsec from Sgr A* would quickly mix in the angular-momentum space, which naturally explains the observed distributions of Wolf-Rayet and OB stars. My results imply that Sgr A* was fueled by gas and stars several millions years ago and could have been an energetic AGN.

2 Fabio Antonini

2.1 Title

Black hole mergers and blue stragglers from hierarchical triples formed in globular clusters

2.2 Abstract

Hierarchical triple-star systems are expected to form frequently via close binary-binary encounters in the dense cores of globular clusters. In a sufficiently inclined triple, gravitational interactions between the inner and outer binary can cause large-amplitude oscillations in the eccentricity of the inner orbit (Lidov-Kozai cycles), which can lead to a collision and merger of the two inner components. In this talk I will discuss results from Monte Carlo models of globular clusters and detailed 3-body simulations that allowed us to place constraints on the importance of Lidov-Kozai-induced mergers for producing: (i) gravitational wave sources detectable by Advanced LIGO, for triples with an inner pair of stellar black holes; and (ii) blue straggler stars, for triples with main-sequence-star components.

3 Arash Bahramian

3.1 Title

Population of X-ray binaries in globular clusters and role of cluster properties in their formation

3.2 Abstract

X-ray binaries (XRBs) are systems containing a compact object (white dwarf, neutron star or black hole) accreting from a companion star. These binaries are orders of magnitude more abundant in globular clusters (GCs) than the rest of our Galaxy. This over-abundance is caused by the high stellar density in GCs, which leads to the formation of XRBs through dynamical encounters. The population of XRBs in GCs shows additional dependences on GC properties such as mass, density, and metallicity, which can illuminate details of XRB formation and destruction processes. We have studied and quantified correlations between populations of XRBs in GCs, and GC properties (based on observational data), using Bayesian Markov-Chain Monte-Carlo techniques. In our study we consider binary formation by dynamical encounters, primordial binaries, and binary destruction.

4 Holger Baumgardt

4.1 Title

The formation of the smallest galaxies

4.2 Abstract

Ultracompact dwarf galaxies (UCDs) are among the densest stellar systems in the Universe. With typical masses of 10^7 to 10^8 solar masses and half-mass radii between 10 to 100 pc they are more than a factor 1000 denser than dwarf galaxies of the same mass. They also show evidence for elevated mass-to-light ratios, which could be due to the presence of massive black holes or unusual stellar IMFs as a result of their extreme densities. While the first UCD was discovered only 15 years ago, hundreds of of them have meanwhile been found in nearby galaxy clusters, making it all the more important to understand where UCDs come from. In my talk I will discuss our current knowledge about UCDs and the various formation channels that have been suggested for them, and explain what we can learn from UCDs about the early evolution of galaxies and the formation of globular clusters.

5 Paolo Bianchini

5.1 Title

A novel look at energy equipartition in globular clusters

5.2 Abstract

Two-body interactions play a major role in shaping the structural and dynamical properties of globular clusters (GCs) over their long-term evolution. In particular, GCs evolve toward a state of partial energy equipartition that induces a dependence of the kinematics on stellar mass. By using a set of Monte Carlo simulations, we show that the mass dependence of the velocity dispersion can be described by an exponential function with one parameter indicating how close to full equipartition the systems are. This simple parametrization successfully captures the behavior of the velocity dispersion both at lower and higher masses, i.e., the regime where the system is expected to approach full equipartition. Moreover we find that, considering all simulations at the same time-snapshot, the level of partial energy equipartition reached by a GC correlates with its concentration, with more concentrated GCs being closer to full equipartition. This correlation may be interpreted as a representation of the relaxation conditions of the systems, and, in principle, can allow to characterize the dynamical state of a cluster on the sole basis of photometric measurements. Finally, this result will be crucial for the understanding of the state-of-the-art proper motion data, for which the mass dependence of kinematics is now measurable, and for the application of modeling techniques which take into consideration multi-mass components and mass segregation.

6 Tjarda Boekholt

6.1 Title

The Origin of Chaos in the Orbit of Comet 1P/Halley

6.2 Abstract

Recent studies have illustrated the chaoticity in comet Halley's orbit with a characteristic Lyapunov time scale of the order its orbital period. To get a better understanding of this short time scale, we construct a new model for the growth of perturbations in a dynamical system. We apply this model to comet Halley and find a Lyapunov time scale of order 300 years, due to strong influences from both Jupiter and Venus.

7 Christian Boily

7.1 Title

A new approach for the assembly of massive star clusters

7.2 Abstract

This talk focuses on the early phase of the formation of a massive cluster. The approach taken borrows from cosmology the idea of following the growth of density fluctuations to setup a fragmented (stellar) system with multiple fragments and a self-consistent velocity field. An adiabatic expansion phase allows low-mass stellar cores to evolve dynamically, which tilts the balance of the stellar mass function towards top-heavy in the final relaxed configuration. Because the relaxation phase is much smoother than one that stems from a cold collapse, there is rapid evolution towards an equilibrium. The characteristics of this equilibrium are therefore more closely correlated with the first $\sim 1Myr$ of the stellar formation epoch.

8 Elisa Bortolas

8.1 Title

Simulations of Massive Black Hole Binaries in Galactic Merger Remnants

8.2 Abstract

Massive black hole binaries are believed to form in the final stages of galaxy mergers. The black hole pairing can be described as a three step process: (i) a dynamical friction dominated phase, (ii) a migration phase induced by slingshot ejections of stars, and (iii) a gravitational-wave driven inspiral leading to rapid coalescence. However, evolution via the slingshot mechanism may be ineffective if the reservoir of interacting stars is not readily replenished, and the binary shrinking may come to a halt at 1 pc separation. Recent simulations suggest that a departure from spherical symmetry in the host system may avoid this stalling. Such asymmetries might be driven, e.g., by a merger. However, current N-body simulations of mergers hit serious problems: the maximum achievable resolution is still below the optimal one, and spurious low-N effects might invalidate the aforementioned results. In this talk, I will show the results of a suite of galaxy-merger N-body simulations, to test the influence of resolution effects on the black hole pairing. In particular, I will discuss the consequences of the artificially enhanced binary Brownian motion resulting from these simulations.

9 Ian Claydon

9.1 Title

The effect of energetically unbound stars on globular cluster kinematics.

9.2 Abstract

Several star clusters show a roughly flat velocity dispersion profile at large radii, which is not predicted from self-consistent models with a tidal truncation (such as 'King models'). This non-zero temperature of stars has previously been attributed to deviations from Newtonian gravity in the weak acceleration regime, but it could also be due to an additional, non-baryonic dark matter component. We investigate the kinematics of stars near the edges of globular clusters assuming Newtonian dynamics and considering collisional N-body dynamics in different galactic tidal fields. We find that the flattening of the velocity dispersion can be explained by stars within the tidal radius of the cluster that have an energy slightly in excess of the critical energy of escape, known as potential escapers. Due to only being able to escape form the Lagrange points, their timescale of escape is long enough to have a measurable effect on the kinematics in the outer parts of the cluster. We derive a scaling for the velocity dispersion of these stars, as a function of clusters mass, which is remarkably close to what modified Newtonian dynamics predicts: $v_{\rm rms}$ proportional to $M^{1/4}$. However, there is an additional dependence on the details of the orbit of the cluster around the galaxy center, which can be used to discriminate between the scenarios and looked for in clusters at different galactocentric radii. Furthermore, we quantify additional kinematic properties of these stars, such as the rotation and anisotropy of the dispersion to determine what we should expect to observe in a potential escaper dominated region. Not including these stars when modeling globular cluster kinematics with equilibrium (self-consistent) models, can lead to a false detection of a dark matter halo, or misinterpretation of the underlying gravity law.

10 Filippo Contenta

10.1 Title

The origin of extended faint stellar systems in the outer Milky Way halo

10.2 Abstract

In a luminosity vs half-light radius diagram, globular clusters and dwarf galaxies are separated in radius at high luminosities (Mv ¡ -4 mag). At fainter luminosities, however, these two types of objects overlap at half-light radii of about 20 to 30 pc ("extended faint stellar systems"). These objects could either be dark matter dominated galaxies, or star clusters.

To understand the origin of these objects we performed a survey of direct N-body simulations, in a Milky Way-like potential, of clusters that dissolve between 8 and 12 Gyr. Taking into account all the observational biases (observable stars, background stars, different lines-of-sight and binaries), we concluded that it is very unlikely that star clusters contribute to the extended faint stellar system population. Because to appear extended a cluster needs to be near apocentre, orbit within the scale radius of the Galactic potential and observed along the orbit.

We considered various shapes of the galactic potential (spherical, oblate and tri-axial), and also allowed the potential to grow in time using time dependent functional form motivated by cosmological models.

In conclusion, we find that the Galactic potential plays a key role on the expansion of the faint stellar systems.

11 Melvyn Davies

11.1 Title

Close encounters involving black holes within stellar clusters

11.2 Abstract

Close encounters between stars will be common in the cores of dense stellar clusters. We consider here encounters between stellar binaries and stellar-mass black holes. In particular we model encounters considering the processes which are likely to produce X-ray binaries which contain black holes.

12 Peter Eggleton

12.1 Title

Probable mergers that turn triples into binaries.

12.2 Abstract

Analysis of 53 fairly wide binaries, where one star is already a red giant, shows two anomalous cases where the secondary is considerably evolved, and yet not massive enough to have evolved significantly. I attribute this to the possibility that the primary is the merger product of what was once a close sub-binary.

13 Michael Fellhauer

13.1 Title

Survival of Young Stellar Clusters

13.2 Abstract

I will present the latest results from our group in Concepcion. We have included a Kroupa IMF in our fast simplified simulations and investigate the changes introduced to our results obtained with equal mass studies of fractal star distributions. We also address the effects of mass segregation. We also embarked on simplified N-body-SPH models (using AMUSE). In those models we try to follow the dynamics of the newborn stars with high precision (direct N-body) rather than focusing on the gas.

14 Francesco Ferraro

14.1 Title

Blue Stragglers as tracers of the internal dynamical evolution of stellar systems

14.2 Abstract

In this talk I present an overview of the main observational properties of a special class of exotic objects (the so-called Blue Straggler Stars, BSSs) in Galactic globular glusters. These properties are discussed in the framework of globular cluster internal dynamics.

15 Michiko Fujii

15.1 Title

The formation and dynamical evolution of young star clusters

15.2 Abstract

Recent observations have revealed a variety of young star clusters, including embedded systems, young massive clusters, and associations. We study the formation and dynamical evolution of these clusters using a combination of simulations and theoretical models. Our simulations start with SPH simulations of turbulent molecular clouds. The stars are assumed to form in the densest regions in the collapsing cloud after an initial free-fall times of the molecular cloud. The dynamical evolution of these stellar distributions are continued by means of direct N-body simulations. The molecular clouds typical for the Milky Way Galaxy tend to form embedded clusters which evolve to resemble open clusters. The associations were initially considerably more clumpy, but lost their irregularity in about a dynamical time scale due to the relaxation process. The densest molecular clouds, which are absent in the Milky Way but are typical in starburst galaxies, form massive young star clusters. They indeed are rare in the Milky Way. Our models indicate a distinct evolutionary path from molecular clouds to open clusters and associations or to massive star clusters. The mass-radius relation for both types of evolutionary tracks excellently matches the observations.

16 Toshio Fukushima

16.1 Title

Zonal Toroidal Harmonic Expansion of Gravitational Field of General Ring-like Object

16.2 Abstract

We present an expression of the external gravitational field of a general ring-like object with the axial and plane symmetries such as annular disks or oval toroids with an arbitrary density distribution. The main term is that of an infinitely thin ring (Fukushima, 2010, Celest. Mech. Dyn. Astron., 108, 339) representing the limit of zero radial width and zero vertical height of the object. The additional term is derived from a zonal toroidal harmonic expansion of general solution of Laplace's equation outside the Brillouin toroid of the object. The special functions required are the point value and the first-order derivative of the zonal toroidal harmonics of the first kind, namely the Legendre function of the first kind of half integer degree and argument being not less than unity. We developed a recursive method to compute them from two pairs of the seed values explicitly expressed by some complete elliptic integrals, which can be computed precisely and quickly (Fukushima, 2015, J. Comp. Appl. Math., 282, 71). Also, we established a procedure to determine the expansion coefficients from the numerically-integrated potential of the object using the analytical expression of the ring potential. Numerical experiments show that appropriately truncated expansions converge rapidly outside the Brillouin toroid. The truncated expansion can be evaluated so efficiently that, for an oval toroid with an exponentially damping density profile, it is 3000-10000 times faster than the two-dimensional numerical quadrature. In order to enlarge the applicability of the harmonic expansion formalism, we propose an approximation of the gravitational field of a thin accretion disk by a superposition of those of multiple annular toroids with a similar trapezoidal cross section.

17 Yoko Funato

17.1 Title

Probabilities of Findings of Wide SMBH Binaries

17.2 Abstract

Recently, a discovery of one of the most massive blackholes was reported (McConnell et al., 2011, Nature, hereafter MC11). Thay observed kinematic properties of stars around the center of NGC4889 , cD in the Coma cluster, and estimated the mass as 2×10^{10} solar mass.

Using N-body simulations, we reproduce the kinematic property of NGC4889 and found that it's interpreted better as that of a wide BH binary. The life time of the wide binary is enough long.

In this talk, we present an example how the wide binary can be observed and discuss about the probabilities of findings of such a wide SMBH binaries in future observations.

18 Mirek Giersz

18.1 Title

A new scenario for IMBH formation in globular clusters.

18.2 Abstract

I will discuss a new scenario for formation of intermediate mass black holes in globular clusters. In this scenario, intermediate mass black holes are formed as a result of dynamical interactions of hard binaries, containing a stellar mass black hole, with other stars and binaries. I will discuss the necessary conditions to initiate the process of intermediate mass black hole formation and the dependence of its rate of mass increase on the global cluster properties. I will also discuss possible observational imprints of intermediate mass black hole presence in star clusters.

19 Alessia Gualandris

19.1 Title

Collisionless loss-cone refilling: the end of the final parsec problem

19.2 Abstract

Mergers of massive black hole binaries (BHBs) are expected to be a key source of gravitational waves (GWs). However, the expected number and frequency of such mergers remains highly uncertain. This owes to a long-standing puzzle known as the final parsec problem. Gravitational N-body simulations that assume a spherical distribution of stars surrounding the BHB find that the binary stalls when all stars on intersecting orbits have been ejected. This is inconsistent with available observations: every massive galaxy observed to date appears to host a single supermassive black hole, and only a handful of BHB candidates exist.

I will review the final parsec problem and present a new approach to determine whether collisional repopulation of the binary's losscone in non-spherical nuclei is a viable mechanism to drive binary coalescence. I will present results of direct summation N-body simulations of galaxy mergers, performed with phiGRAPE and HiGPUs and running on multiple GPUs. These allow to measure the binary hardening rate and determine a new proxy that depends only on the stars' angular momentum.

I will then present collisionless simulations of spherical and non-spherical isolated models to increase the number of particles sufficiently that collisional effects become unimportant and collisionless losscone refilling can be measured.

20 Hosein Haghi

20.1 Title

The effect of primordial residual-gas expulsion on the stellar mass function slope of globular clusters

20.2 Abstract

We perform a series of direct N-body calculations to investigate the effect of residual gas expulsion from the gas-embedded progenitors of present-day globular clusters (GCs) on the stellar mass function (MF). Our models start either tidally filling or underfilling, and either with or without primordial mass segregation. We cover 100 Myr of the evolution of modeled clusters and show that the expulsion of residual gas from initially mass-segregated clusters leads to a significantly shallower slope of the stellar MF in the low- ($m \leq 0.50 M_{\odot}$) and intermediate-mass ($\simeq 0.50 - 0.85 M_{\odot}$) regime.

Therefore, the imprint of residual gas expulsion and primordial mass segregation might be visible in the present-day MF. We find that the strength of the external tidal field, as an essential parameter, influences the degree of flattening, such that a primordially mass-segregated tidally-filling cluster with $r_h/r_t \geq 0.1$ shows a strongly depleted MF in the intermediate stellar mass range. Therefore, the shape of the present-day stellar MF in this mass range probes the birth place of clusters in the Galactic environment. We furthermore find that this flattening agrees with the observed correlation between the concentration of a cluster and its MF slope, as found by de Marchi et al.. We show that if the expansion through the residual gas expulsion in primordial mass segregated clusters is the reason for this correlation then GCs most probably formed in strongly fluctuating local tidal fields in the early proto-Milky Way potential, supporting the recent conclusion by Marks & Kroupa.

21 Akram Hasani Zonoozi

21.1 Title

The Sizes of Globular Clusters as Tracers of Galactic Halo Potentials

21.2 Abstract

We present N-body simulations of globular clusters, exploring the effect of different galactic potentials on cluster sizes, r_h. For various galactocentric distances, R_G, we assess how cluster sizes change when we vary the virial mass and concentration of the host galaxy's dark-matter halo. We show that different concentrations in a halo of identical mass can determine either the survival or disruption of a star cluster orbiting the host galaxy within the inner $\approx 20\%$ of its virial radius. We find that clusters orbiting in the inner parts of less concentrated haloes are significantly more extended than those evolving in more concentrated haloes, while the final sizes of those orbiting outside 20% of the virial radius are almost independent of the concentration parameter. Adding a baryonic component to our galaxy models does not change these results much, since its effect is only significant in the innermost $\approx 10\%$. Our simulations show that there is a relation between r_h and R_G, which systematically depends on the physical parameters of the halo. Hence, observing such relations in individual galaxies can put a new observational constraint on dark-matter halo characteristics. However, by varying the halo mass in a wide range of $M_{vir} = 10^9 - 10^{13} \mathrm{M}_\odot$, we find that the $r_h - R_G$ relationship will be nearly independent of halo mass, if one assumes M_{vir} and c_{vir} as two correlated parameters, as is suggested by cosmological simulations.

22 Douglas Heggie

22.1 Title

Phase dependence of escape from star clusters on elliptic orbits

23 Jongsuk Hong

23.1 Title

Evolution of binary stars in multiple-population globular clusters

23.2 Abstract

Simulations of the formation of multiple stellar populations in globular clusters predict that second-generation stars form in a compact subsystem in the cluster central regions. Previous studies have suggested that the initial differences in the structural properties of first- and second-generation stars can have significant implications for the evolution of the binary star population.

We have performed a survey of N-body simulations to explore the evolution of binary stars in multiple-population globular clusters. We will presents results concerning the differences in the evolution of the global fraction of first- and second-generation binaries, the evolution of the binary spatial distribution, and of the binary binding energy distribution for clusters with different initial structural properties.

24 Natsuki Hosono

24.1 Abstract

The hydrodynamical simulations of rotating disk play important roles in the field of astrophysical and planetary science. Smoothed Particle Hydrodynamics (SPH) has been widely used for such simulations. It, however, has been known that with SPH, a cold and thin Kepler disk breaks up unphysically. Two possible reasons have been suggested for this break-up of the disk; the artificial viscosity (AV) and the numerical error in the evaluation of pressure gradient in SPH. However, which one is dominant has been still unclear. In this paper, we investigate the reason for the rapid break-up of the disk. We implemented several formulations of AV and switches and measured the angular momentum transfer from both AV and the error of SPH estimate of pressure gradient. We found that the angular momentum transfer due to AV at the inner edge triggers the break-up of the disk. We also found that classical von-Neumann-Richtmyer-Landshoff type AV with high order estimate for $\nabla \cdot \vec{v}$ can maintain the disk for ~ 100 orbits even when used with standard SPF formulation.

25 Piet Hut

25.1 Title

From Astrophysics to Astrobiology to Complex Systems Studies

25.2 Abstract

My most recent journeys have brought me from stellar dynamics to astrobiology, and in particular the question of origins of life. Related to that, I have started to study the spontaneous emergence of autonomous agents in complex systems. I am happy to share some of my adventures in these areas.

26 Arkadiusz Hypki

26.1 Title

Comparing complex numerical models with the Gaia archive

26.2 Abstract

I'm involved in the GENIUS project within the DPAC consortium.

The aim of the GENIUS project is to help to design and implement Gaia archive and in that way to maximize the scientific exploitation of the Gaia data by the astronomical community.

In the talk I would like to present a way to compare complex numerical models with the Gaia archive.

27 Lucie Jilkova

27.1 Title

Mass transfer among debris discs during close stellar encounters

27.2 Abstract

Stars are born in clustered environment and planetary systems are born around stars. Stars in clusters gravitationally interact and experience close encounters that have a direct influence on their planetary systems. We will present results on simulations of mass transfer among debris (planetesimal) discs during close stellar encounters that happen in star clusters. We explored the parameter space of the encounters and mapped the orbits of the transferred planetesimals around their parent star as well as around their new host. We show that, depending on encounter parameters, a substantial part of the disc can be captured by the other star and that the captured objects have specific orbits. We will present the implications of mass transfer during a close stellar encounter for the Solar system.

28 Dongming Jin

28.1 Title

Prospects for observing dynamically formed Black Hole Binaries in the Virgo Cluster with Gravitational Waves.

28.2 Abstract

The dynamical evolution of globular clusters is expected to produce stellar mass binary black holes with higher total mass than found in the field population of binary black holes. These systems may be detectable at extragalactic distances that extend out to the Virgo cluster. I use the Monte Carlo code MOCCA to simulate the production of binary black holes from globular clusters in the Virgo cluster and discuss the prospects for the detection of dynamically formed black hole binaries using gravitational wave detectors.

29 Junko Kominami

29.1 Abstract

We have implemented Ninja algorithm into N-body code for planet accretion using blockstep algorithm. As a result, we succeeded for the first time to simulate planet accretion with high efficiency of parallelization using 10^4 cores. Factor times 10^5 particles can be simulated with such a number of cores since Ninja algorithm is used. Here we summarize the detail of the implementation and the performance results. We achieved 26.8 % of the peak performance on K-computer.

30 Andreas Kuepper

30.1 Title

Dynamics of Outer Halo Globular Clusters

30.2 Abstract

Outer-halo globular clusters are significantly more extended than GCs in the inner galaxy. Based on N-body simulations, I will argue that all GCs were born compact and expanded (or are still expanding) into their available Roche volume. Signs of this process are imprinted in their stellar mass functions, in their surface density profiles, and in their orbital anisotropy profiles. In fact, the de Marchi relation of less concentrated clusters having shallower stellar mass function slopes is a direct consequence of this expansion process. I will point out potential biases in measurements of half-mass radii, velocity dispersions, and mass function slopes for outer-halo satellites.

31 Barbara Lanzoni

31.1 Title

Internal dynamics of Galactic globular clusters: an observational perspective

31.2 Abstract

I will describe a project promising to open a new golden age in the study of the internal dynamics of Galactic globular clusters. The crucial ingredients are (1) a complete radial mapping of each cluster and (2) the use of the radial velocities of hundreds individual stars (instead of integrated-light spectroscopy). To reach these goals, we use a coordinated combination of different multi-object spectrographs: adaptive-optics assisted IFU for the innermost cluster regions, multi-arm deployable IFU for the intermediate radii, and multi-fiber spectroscopy out to the tidal radii. Together with parallel programs aimed at determining the stellar proper motions and a new generation of star density profiles, the project is expected to finally answer long-lasting questions ranging from the presence of pressure anisotropy and rotation, up to the existence of intermediate-mass black holes and dark matter halos in globular clusters, with a major impact in several areas of modern Astrophysics.

32 Nathan Leigh

32.1 Title

Missing Ingredients in Numerical Recipes for Star Cluster Evolution

32.2 Abstract

In this talk, I will address several aspects of the question: What is missing from modern day simulations of star clusters? I will review the basic assumptions implemented in both N-body and Monte Carlo models for star cluster evolution, in particular those related to stellar and binary evolution, strong gravitational encounters and cluster mass loss. The validity of these assumptions is then quantified as a function of the host cluster environment. It is shown that many of the standard assumptions implemented in the globular cluster regime break down in low-mass open clusters, giving rise to what is arguably a richer and more complicated dynamical environment. Finally, I will present a robust method for deriving the initial total stellar masses in star clusters, for any combination of observed cluster parameters (e.g. mass, density, orbit, etc.). By applying this method to roughly 30 Galactic globular clusters, I will illustrate that both N-body and Monte Carlo simulations for cluster evolution are in many cases significantly under-estimating the mass loss.

33 Jun Makino

33.1 Title

N-body simulation on general- and special-purpose supercomputers.

33.2 Abstract

I'll overview the last thirty years of the history of (mostly direct) N-body simulations, on various kinds of supercomputers such as vector machines, early parallel computers, GRAPEs, GPGPUs, and large MPP systems.

34 Steve McMillan

34.1 Title

A Hybrid Journey: From Stellar Dynamics to Cluster Formation

34.2 Abstract

Star cluster formation is a complex astrophysical problem combining multiple competing physical processes in a challenging computational environment. Current simulations still fall short of a realistic description of the many processes at work in star-forming regions. We are developing a hybrid simulation code to explore the formation of and gas ejection from massive star clusters by combining the magnetohydrodynamics code Flash and the AMUSE software environment. Radiative, wind, and supernova feedback are followed in FLASH based on stellar information provided by the AMUSE system. I will present a highly personal and completely unprofessional view of some of the software developments over the past 3 decades that ultimately contributed to the creation of AMUSE, and will discuss the early stages of the current project, focusing on cluster formation and assembly and the incorporation of stellar feedback to study gas expulsion and cluster survival.

35 Yohai Meiron

35.1 Title

Expansion Techniques for Collisionless Stellar Dynamical Simulations

35.2 Abstract

We present ETICS, a collisionless N-body code based on two kinds of series expansions of the Poisson equation, implemented for graphics processing units (GPUs). The code is publicly available and can be used as a standalone program or as a library: we show results from a hybrid between ETICS and the phiGRAPE direct N-body code, as well as an AMUSE plugin (which is packaged with the code). One of the two expansion methods available is the self-consistent field (SCF) method, which is a Fourier-like expansion of the density field in some basis set; the other is the multipole expansion (MEX) method, which is a Taylor-like expansion of the Green's function. MEX, which has been advocated in the past, has not gained as much popularity as SCF. Both are particle-field methods and optimized for collisionless galactic dynamics, but while SCF is a "pure" expansion, MEX is an expansion in just the angular part; thus, MEX is capable of capturing radial structure easily, while SCF needs a large number of radial terms.

36 Marco Merafina

36.1 Title

Gravity and thermodynamics: a new point of view in the analysis of equilibrium and dynamical evolution of globular clusters.

36.2 Abstract

In the analysis of the evolution of globular clusters, stellar encounters strongly contribute in phase space mixing of stellar orbits. In this scenario, thermodynamics plays a central role in the gravitational equilibrium and stability of the clusters, being binary relaxation time shorter than the age of such systems. On the other hand, the observations of luminosity profiles of globular clusters, at different values of the central gravitational potential, show self similar curves that suggest a unique distribution function with changing thermodynamical parameters during the dynamical evolution, according to the numerical simulations existing in literature. This means that the evolution of globular clusters can be studied by considering small thermodynamic transformations which keep constant the functional form of the velocity distribution of stars like in the framework of Boltzmann statistical mechanics.

Here we construct models with a different approach by applying thermodynamic principles to a Boltzmann distribution function with an Hamiltonian function which contains an effective potential depending on the kinetic energy of the stars, due to the effect of tidal interactions induced by the hosting galaxy. The Hamiltonian function is solution of the Fokker-Planck equation solved in a different way with respect to the King approach.

Thus, we obtain new relations for the thermodynamical equilibrium in presence of a gravitational potential, a different form of the virial theorem, and introduce the concept of thermodynamical and kinetic temperature, pressure and chemical potential (intensive quantities).

In addition, we can show that a globular cluster can be described as a model containing regions with positive and negative specific heat producing thermodynamic instabilities which drive the systems towards the gravothermal catastrophe, without the necessity of an external thermal bath.

The influence of the effective potential on the virial theorem will be described, together with the related consequences on the gravothermal stability limits for star clusters. This new limit is different from one obtained by Katz in 1978 and in complete accordance with the value related to the maximum of clusters distribution constructed by data from Harris Catalogue for globular clusters. This agreement between theory and observations is obtained also for small clusters, giving the conditions for the disruption of clusters, never obtained from the theoretical point of view.

Finally, new developments on N-body simulations for glubular clusters (GC) are presented. The results confirm the theory of the effective potential arising from the presence of tidal interactions between the cluster and the hosting galaxy.

37 Shugo Michikoshi

37.1 Title

Galactic Spiral Arms by Swing Amplification

37.2 Abstract

Based on the swing amplification model, we investigate the formation and structure of stellar spirals in disk galaxies. We calculate the pitch angle, wavelengths, and amplification factor of the most amplified mode from the linear theory. We obtain the fitting formulae of these quantities as a function of the epicycle frequency and Toomre's Q. As the epicycle frequency increases, the pitch angle and radial wavelength increases, while the azimuthal wavelength decreases. The amplification factor decreases with Q rapidly. In order to check the validity, we perform N-body simulations. These dependencies agree with those by N-body simulations. Using these results, we estimate the number of spiral arms as a function of the shear rate. The number of spiral arms increases with the shear rate if the disk to halo mass ratio is fixed.

38 Meghan Miholics

38.1 Title

The Dynamics of Multiple Populations in the Globular Cluster NGC 6362

38.2 Abstract

We investigate how the Milky Way tidal field can affect the spatial mixing of multiple stellar populations in the globular cluster NGC 6362. We use N-body simulations of multiple population clusters on the orbit of this cluster around the Milky Way. Models of the formation of multiple populations in globular clusters predict that the second population should initially be more centrally concentrated than the first. However, NGC 6362 is comprised of two chemically distinct stellar populations having the same radial distribution. We show that the high mass loss rate experienced on this cluster's orbit significantly accelerates the spatial mixing of the two populations expected from two body relaxation. We also find that for a range of initial second population concentrations, cluster masses, tidal filling factors and fraction of first population stars, a cluster with two populations should be mixed when it has lost 70-80 per cent of its initial mass. These results fully account for the complete spatial mixing of NGC 6362, since, based on its shallow present day mass function, independent studies estimate that the cluster has lost 85 per cent of its initial mass.

39 Domenico Nardiello

39.1 Title

Multiple Stellar Populations in Globular Cluster: last results

39.2 Abstract

Globular clusters represent an ideal laboratory to understand stellar formation and evolution, and chemical enrichment in the primordial Universe, and, for this reason, these objects are a reference point in cosmologic and stellar evolution theories. The discovery of multiple stellar populations in all the globular clusters, characterized by different chemical properties, has revitalized the interest in these objects. In my talk I will present the last results regarding the multiple stellar populations in some globular clusters, obtained thanks the recently collected HST UV data.

40 Keigo Nitadori

40.1 Title

10th- and 12-th order Hermite integrators, and more.

40.2 Abstract

The computational cost for up to the p-th order derivatives of Newtons's gravitational force is $O(p^2)$, and does not grow exponentially. Thus, we can easily construct $2(p+1)$-th order Hermite integrator in a reasonable cost. We show some preliminary result of the 10th- and 12th-order integrators.

41 James Petts

41.1 Abstract

I present a new semi-analytic model for dynamical friction and implement it in the direct summation code, NBODY6 (Petts, Gualandris & Read 2015, submitted). My model is based on the familiar Chandrasekhar formalism. However, the key novelty is new physically motivated maximum and minimum impact parameters. These give an excellent match to full N-body simulations for both cuspy and shallow background density distributions, without any fine-tuning of the model parameters. In particular, my model is able to reproduce the dramatic core-stalling effect that occurs in shallow/constant density cores, for the first time. My implementation in NBODY6 allows one to efficiently model the orbital decay of a star cluster moving in a background distribution of stars, since only the cluster particles need to be integrated with the direct summation code. This approach has a broad range of astrophysical applications from studying dynamical friction on young clusters near the Galactic Centre, to modelling globular clusters and dwarf galaxies moving within the Galaxy. Using this approach, I also present a study of the young stellar population in the Galactic Centre.

42 Giampaolo Piotto

42.1 Title

Photometric and spectroscopic properties of multiple stellar sopulations in Galactic globular glusters: implications for the formation scenarios

42.2 Abstract

Some of the proposed scenarios able to account for the photometric and chemical properties of multiple stellar populations in globular clusters imply that these objects must have been much more massive in the past. Whether globular clusters should be considered either as remnants of massive star clusters or nuclei of former dwarf galaxies is an open issue, and both possibilities may be valid. Surely, in order to shed light on this problem, we need to better know the chemical and kinematical properties of the different populations hosted by single clusters, and their relation with the cluster parameters,

In my talk, I will present an updated review on the frequency of multiple populations in globular clusters of our Galaxy, on their chemical tagging, radial distribution and kinematics. The relation between multiple population properties and cluster parameters will be illustrated. Consequences of these observational facts on different scenarios proposed for the formation and evolution of globular cluster stars will be critically discussed. Future perspectives towards our understanding if this complex phenomenon will be highlighted.

43 Simon Portegies Zwart

43.1 Title

Reconstructing the Trapezium cluster by dynamical disk-truncating interactions in the young star cluster

43.2 Abstract

We compare the observed size distribution of circum stellar disks in the Orion Trapezium cluster with the results of N-body simulations in which we incorporated an heuristic prescription for the evolution of these disks. In our simulations, the sizes of stellar disks are affected by close encounters with other stars (with disks). We find that the observed distribution of disk sizes in the Orion Trapezium cluster is excellently reproduced by truncation due to dynamical encounters alone. The observed distribution appears to be a sensitive measure of the past dynamical history of the cluster, and therewith on the conditions of the cluster at birth. The best comparison between the observed disk size distribution and the simulated distribution is realized with a cluster of $N = 2500 \pm 500$ stars with a half-mass radius of about 0.5 pc in virial equilibrium (with a virial ratio of $Q = 0.5$, or somewhat colder $Q \simeq 0.3$), and with a density structure according to a fractal dimension of $F \simeq 1.6$. Simulations with these parameters reproduce the observed distribution of circum stellar disks in about 0.2–0.5 Myr.

44 Florent Renaud

44.1 Title

Star clusters in cosmological context

44.2 Abstract

The formation and evolution of star clusters is closely linked to that of galaxies. Because of the huge dynamical range involved, modelling both aspects at once is a major challenge of modern astrophysics. Pioneer studies focused on the co-evolution of clusters with their galaxies, and their response to either the long-term, adiabatic evolution of their hosts, or more violent events like mergers. However, up to now technical limitations have prevented considering the full history of clusters from birth to dissolution in a self-consistent way. Thanks to recent developments in computational astrophysics, we are now able to bridge this gap and explore cluster evolution, including their formation, in cosmological context. In this talk, I will review the key studies that helped us to understand the building blocks of star cluster evolution. I will then present new work combining all these effects together, and discuss their relative importance, as a function of cosmological and galactic environment.

45 Harvey Richer

45.1 Title

Stellar Dynamics Informing Stellar Evolution

45.2 Abstract

In this talk I will give examples of how stellar dynamics in the core of a globular cluster can lead to new insights into stellar evolution. Examples will be chosen from white dwarf stars, asymptotic giant branch stars, horizontal branch stars and blue stragglers.

46 Steven Rieder

46.1 Title

The strange ring around stellar companion J1407b

46.2 Abstract

J1407 (1SWASP J140747.93-394542.6 in full) is a young star in the Scorpius-Centaurus OB association that underwent a series of complex eclipses over 56 days in 2007. In a series of articles, Mamajek et al. and others hypothesised that a secondary substellar companion, J1407b, has a giant ring system filling the Hill sphere, and this caused the eclipses. Observations have not successfully detected J1407b, but do rule out circular orbits for the companion around the primary star. I will show the results of simulations run with the AMUSE framework, used to test the stability of Hill sphere-filling ring systems when the companion is on an eccentric orbit.

47 Alison Sills

47.1 Title

The Evolution of Young Stellar Complexes in the Milky Way

47.2 Abstract

Observations of local young star-forming regions reveal significant substructure in their stellar populations, including chain structures along molecular filaments, clumpy clusters, and sub-clusters in a smooth background of stars. They also still contain significant amounts of gas & dust. Slightly older open clusters are almost always spherical and reasonably well described by a cored density structure, and have lost almost all their gas. In this work, we use observationally-motivated initial conditions for small clusters including both gas and stars. Using AMUSE, we evolve the system until the point of the first supernova. We explore the changing morphologies of the stellar systems and look at the dynamical evolution of the gas. Our results can be applied to understand the effects of initial conditions on the early evolution of star clusters of varying masses and ages.

48 Mario Spera

48.1 Title

Do open clusters evolve toward energy equipartition?

48.2 Abstract

According to kinetic theory of stellar systems, if stars follow a realistic mass function, gravitational encounters tend to establish equipartition of kinetic energy. At equipartition, the mean-square velocity scales inversely with the mass of the star. To investigate the degree of energy equipartition we expect from observations of stellar systems, I performed a large number of direct-summation N-body simulations of open clusters, using a modified version of the STARLAB software environment. This version includes up-to-date recipes of stellar evolution, black holes and neutron stars birth kicks and advanced prescriptions for supernova explosions. In this talk I show that the degree of energy equipartition depends on the initial positions and velocities of stars, on the slope of the initial mass function, on the effect of a galactic tidal field and on stellar evolution. I found that all simulated systems are very far from equipartition, and do not tend to equipartition even after many relaxation times. Finally, I make predictions on the dynamical state of open clusters in the Milky Way.

49 Rainer Spurzem

49.1 Title

Supermassive Black Hole Binaries in Galactic Nuclei and Gravitational Wave Emission, simulated on large GPU clusters

49.2 Abstract

Many if not all galaxies contain single or multiple supermassive black holes (SMBH). We study the formation and evolution of supermassive binary black holes, their final merger by relativistic coalescence, and the effect on tidal disruptions. Relativistic corrections to Newtonian dynamics (so-called Post-Newtonian approximations) have to be taken into account to follow the dynamics of binaries with compact remnants (black holes, neutron stars).

Spin-Spin and Spin-Orbit interactions are also considered.

We discuss the gravitational wave emission of stellar mass black holes and supermassive black holes through ground based or space based current and future detectors. Gravitational wave astronomy will become in the future as rich as electromagnetic astronomy. The use of accelerated computing (currently: GPU) for astrophysical computations at National Astronomical Observatories of Chinese Academy of Sciences is presented. We discuss detailed timing models for some codes and future perspectives towards Exaflop/s.

50 Anna Lisa Varri

50.1 Title

Long-term evolution of star clusters: rotation and tides

50.2 Abstract

By means of N-body simulations, we explore the long-term dynamical evolution of star clusters, considered either in isolation or in the presence of an external tidal field, and characterized by a broad range of different initial structural and kinematical properties, including the presence of differential rotation. We will discuss the role of angular momentum in the evolution toward core collapse, by comparing the local and global properties of rotating and non-rotating stellar systems with similar initial structure. Particular attention will also be given to the analysis of the interplay between rotation and tides, and their effects on the anisotropy in the velocity space of the systems. Specifically, we will show that the evolution of the anisotropy strength and its radial variation within a cluster may contain distinct imprints of the cluster initial structural properties and dynamical history.

51 Eugene Vasiliev

51.1 Title

Evolution of binary supermassive black holes and the mythical final-parsec problem

51.2 Abstract

I review the evolution of binary supermassive black holes, driven by encounters with stars of the galactic nucleus, and focus on the stellar-dynamical solution to the "final-parsec problem". The problem itself arises in idealized spherical systems in which the reservoir of stars that are able to interact with the binary via three-body slingshot is severely depleted, leading to a very slow evolution. Recent N-body simulations have suggested that in non-spherical systems the evolution occurs much more rapidly due to enhanced angular momentum exchange. However, it remained unclear to what extent these results are affected by collisional relaxation, which is much stronger in simulations than in real galaxies.

We address this problem using a new Monte Carlo simulation method that can deal with non-spherical galaxies and takes both collisional and collisionless processes into account in an adjustable proportion. We demonstrate that in the purely collisionless limit, the final-parsec problem still exists in spherical and axisymmetric systems, but even a minor deviation from axisymmetry is sufficient for the problem to disappear, i.e. for the binary to merge within a Hubble time. We also show that conventional N-body simulations cannot at present accurately model these effects, being dominated by numerical relaxation.

52 Joshua Wall

52.1 Abstract

We present a method for coupling the magnetohydrodynamics code Flash to various N-body solvers in the AMUSE framework using a gravity bridge (Wisdom and Holman 1991, Fujii 2007). We demonstrate that both energy and momentum are conserved by this technique when evolving stars and gas together. Further, we show how any violation of the symmetry of the gravity solver used to calculate the gravity bridge kicks spoils momentum conservation. Finally, we report on progress in using this method to simulate the formation of young massive clusters from giant molecular clouds.

53 Long Wang

53.1 Title

The title: DRAGON GC simulation project: million-body simulation of globular clusters

53.2 Abstract

Abstract: Introducing the DRAGON simulation project, we present direct N-body simulations of four massive globular clusters (GCs) with 106 stars and 5% primordial binaries at an high level of accuracy and realism. The GC evolution is computed with NBODY6++GPU and follows the dynamical and stellar evolution of individual stars and binaries, kicks of neutron stars and black holes, and the effect of a tidal field. We investigate the evolution of the luminous (stellar) and dark (faint stars and stellar remnants) GC components and create mock observations of the simulations (i.e. photometry, color-magnitude diagrams, surface brightness and velocity dispersion profiles). Connecting internal processes to observable features we highlight the formation of a long-lived 'dark' nuclear sub-system made of black holes (BHs), which results in a two-component structure. The inner core is dominated by the BH subsystem and experiences a core collapse phase within the first Gyr. It can be detected in the stellar (luminous) line-of-sight velocity dispersion profiles. The outer extended core - commonly observed in the (luminous) surface brightness profiles - shows no collapse features and is continuously expanding. We demonstrate how a King (1966) model fit to observed clusters might help identifying the presence of post core-collapse BH subsystems. For global observables like core and half-mass radii the direct simulations agree well with Monte-Carlo models (MOCCA-code). Variations in the initial mass function can result in significantly different GC properties (e.g. density distributions) driven by varying amounts of early mass loss and the number of forming BHs.

54 Thomas Wijnen

54.1 Title

Face-on accretion onto Protoplanetary Discs: Implications for Globular Cluster Evolution

54.2 Abstract

In the past decade, observational evidence that Globular Clusters (GCs) harbour multiple stellar populations has grown steadily. These observations are hard to reconcile with the classic picture of star formation in GCs, which approximates them as a single generation of stars. Bastian et al. recently suggested an evolutionary scenario in which a second (and higher order) population is formed by the accretion of chemically enriched material onto the low-mass stars in the initial GC population. In this early disc accretion scenario the low-mass, pre-main sequence stars sweep up gas expelled by the more massive stars of the same generation into their protoplanetary disc as they move through the cluster centre. Using assumptions that represent the (dynamical) conditions in a typical GC, we investigate whether a low-mass star surrounded by a protoplanetary disc can indeed accrete sufficient enriched material to account for the observed abundances in 'second generation' stars. We compare the outcome of two different smoothed particle hydrodynamics codes and check for consistency. In particular, we focus on the lifetime and stability of the disc and on the gas accretion rate onto both the star and the disc.

55 Satoko Yamamoto

55.1 Abstract

Mesh-free methods for compressive fluids are widely used for fluid simulations in which large deformations occur. However, traditional mesh-free methods cannot accurately handle free surfaces or discontinuities, where the pressure distribution is not differentiable. There are two causes for this limitation. First, a lot of traditional methods directly derive the density element instead of using the equation of continuity. However, the approximation formula does not satisfy partition of unity, causing an error. Second, traditional methods use a low order formula for approximating the physical quantities gradient. Therefore, they cannot formulate the equations of motion and energy correctly.

To solve these problems, we present a high-order mesh-free method for compressive fluid. As a solution for the first problem, we integrate the equation of continuity in the new method. In addition, for the second problem, we apply a high-order approximation formula of Tamai et al. (2013). They derived this high-order formula for uncompressive fluids by Taylor expansion of the physical quantity term in the low-order formula. By deriving high-order terms with Taylor expansion, the formula can handle arbitrary order modes of physical quantities with arbitrary particle distributions in finite order.

We also compare the results of numerical tests of our new method, using a second order approximation formula, to the results of traditional methods. These results show that our method can handle free surfaces and discontinuities better than, or at least as good as, traditional methods. However, the new method cannot accurately handle discontinuities with indifferentiable pressure distributions, because these distributions have infinite space order. Therefore, we need other prescriptions for these discontinuities, which we will address in future work.

56 Denis Yurin

56.1 Title

An iterative method for the construction of N-body galaxy models in collisionless equilibrium

56.2 Abstract

We describe a new iterative approach for the realization of equilibrium N-body systems for given density distributions. Our method uses elements of Schwarzschild's technique and of the made-to-measure method, but is based on a different principle. Starting with some initial assignment of particle velocities, the difference of the time-averaged density response produced by the particle orbits with respect to the initial density configuration is characterized through a merit function, and a stationary solution of the collisionless Boltzmann equation is found by minimizing this merit function directly by iteratively adjusting the initial velocities. Because the distribution function is in general not unique for a given density structure, we augment the merit function with additional constraints that single out a desired target solution. The velocity adjustment is carried out with a stochastic process in which new velocities are randomly drawn from an approximate solution of the distribution function, but are kept only when they improve the fit. Our method converges rapidly and is flexible enough to allow the construction of solutions with third integrals of motion, including disc galaxies in which radial and vertical dispersions are different. A parallel code for the calculation of compound galaxy models with this new method is made publicly available.

57 Alice Zocchi

57.1 Title

Pressure anisotropy in globular clusters

57.2 Abstract

Pressure anisotropy plays an important role in the dynamics of globular clusters, and it should be taken into account to properly describe these systems during their evolution. Nowadays, this is particularly important because the upcoming measurements of proper motions by HST and GAIA will soon enable us to directly measure the anisotropy content of globular clusters, thus providing further information on their dynamical state. Understanding the dynamics of a cluster as a whole is crucial when considering the degeneracy between the feature generated by pressure anisotropy in the projected velocity dispersion profile and the one due to the presence of an intermediate-mass black hole in the centre of the system. As an example, we discuss the case of Omega Cen.